

Seismic constraints on the present-day kinematics of the Gargano foreland, Italy, at the transition zone between the southern and northern Apennine belts

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[1] The 1995–2004 seismicity in the Gargano Promontory (hereafter GP) foreland at the transition zone between Southern and Northern Apennine belts (Italy) is analyzed with the aim to put constraints on the present-day kinematics of this key-area of the foreland. The spatial distribution of earthquakes and 54 calculated focal mechanisms show that the main GP ruptures develop along E-W striking, right-lateral strike-slip faults and NW-SE, normal to left-lateral second-order faults that move in response to a prevailing NW-SE compression (i.e. NE-SW extension). Tacking into account the depth of the relocated seismicity and the available geological information, we propose that the GP shear zone represents an E-W striking, major crustal discontinuity separating sectors of the foreland that move in response to the higher, northeastward propagation velocity of the thrust front of the Northern Apennines with respect to that of the Southern Apennines. **Citation:** Milano, G., R. Di Giovambattista, and G. Ventura (2005), Seismic constraints on the present-day kinematics of the Gargano foreland, Italy, at the transition zone between the southern and northern Apennine belts, *Geophys. Res. Lett.*, 32, LXXXXX, doi:10.1029/2005GL024604.

1. Introduction

[2] The Gargano Promontory (hereafter GP) is located in the Apulian platform, a part the Adriatic Plate that represents the foreland of the NE-verging, Neogene Apennines thrust belt. The inner sectors of Apennines are affected by a NE-SW striking extension, whereas the external thrusts propagate on the foreland region (Figure 1a) [Doglioni *et al.*, 1994]. GP represents a key-area of the foreland because it is placed near the zone where the external thrusts of Northern Apennines merge those of Southern Apennines (Figure 1b). In addition, GP separates the northern edge of the Apulian foreland, which is experiencing an important uplift from Early Pliocene times, from the still subsiding Northern Adriatic foreland (Figure 1a) [Doglioni *et al.*, 1994]. Brankman and Aydin [2004] propose that GP uplift is a push-up related to E-W striking, left-lateral strike-slip faults. Chilovi *et al.* [2000] and Borre *et al.* [2003] report that from Late Pliocene to Quaternary, the E-W faults are reactivated with dextral slips. The GP uplift results from the buckling of Apulian foreland due to the higher hinge

rollback of the northern Adriatic lithosphere with respect to the southern one [Doglioni *et al.*, 1994]. According to Valensise *et al.* [2004], the GP, E-W striking faults propagate westward beneath Southern Apennines and are responsible for the 2002, $M_W = 5.7$ earthquake (Figure 1b).

[3] The seismicity and kinematics of GP and of the sector between GP and the Southern Apennines are surprisingly poorly known because of the lack of studies on the relations between seismicity and tectonic structures. Historically, an $I_o = X$ MCS earthquake struck the area in 1627 (Figure 1b) [Gruppo di Lavoro CPTI, 1999; Patacca and Scandone, 2004] causing more than 5000 victims and a resulting tsunami affected the northern GP coast. Moderate ($I_o = VII-VIII$ MCS) earthquakes also occurred in the area (Figure 1b). Since 1975, the instrumental catalogue [Castello *et al.*, 2005] shows that the GP area is characterized by isolated low magnitude events ($M_{Dmax} = 3.5$), but a major activity occurred in 1995 with a seismic sequence started with a main, $M_W = 5.2$ event. Due to the few seismic stations running in the area before 1995, reliable hypocenter locations and well constrained focal mechanisms are not available. Here, we study the seismicity occurred in the GP sector of the foreland between 1995 and 2004. The increasing number of nationwide seismic stations in the last 10 years ensures accurate earthquake locations and focal mechanisms that may yield new constraints on the present-day geodynamics of the foreland.

2. Data and Analytical Methods

[4] We used data recorded by the Italian Telemetered Seismic Network (ITSN) operated by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) and by the Osservatorio Vesuviano network (OV-INGV). When available, we also used data recorded by surrounding European seismic networks (Figure 1a) as well as data from temporary local seismic stations (Figure 2). Currently, the ITSN consists of more than 100 analogue and digital mono and three component stations equipped with two types of instruments: short-period Geotech S-13, and broadband sensors installed in the last 5 years. The OV-INGV regional real-time seismic network has similar characteristics as ITSN.

[5] We collect the digital waveforms of all available data to perform accurate re-picking in order to increase the precision of the P- and S-phase arrival time, and to obtain P-wave first motion polarities. To achieve reliable and accurate hypocenter locations, we selected the seismic events with at least six P and four S arrival times. We relocate the seismic events by means of the standard HYPO71 algorithm [Lee and Lahr, 1975] because the study area is quite extended and the velocity model is not well

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resolved [Venisti *et al.*, 2005]. Tests performed considering the distribution of events and seismic stations evidenced that the use of more sophisticated location methods, e.g. the Joint Hypocenter Determination [Douglas, 1967; Console *et al.*, 1992], or the double difference method [Michellini and Lomax, 2004], does not produce substantial improvements in the accuracy of the locations. We used, as initial, the 1D velocity model given by Console *et al.* [1992]. To improve the earthquake locations with respect the starting velocity model, we performed some trials on about 100 events occurred sparsely in the study area. We relocated this restrict data-set with a new 1D velocity model constructed perturbing the starting model with the available velocity fields from analysis of DSS data [Scarascia *et al.*, 1994] and teleseismic tomography [De Gori *et al.*, 2001]. The obtained velocity model used to relocate the entire data-set is reported in Table 1. With respect to the starting velocity model, this latter minimizes the residuals at the seismic stations located at regional distance, gives lower relative errors on event locations (hypocentral errors less than ± 2.5 km; RMS values less than 0.5 s), and shows less scatters on the depth of the events.

[6] Best fit, double-couple focal mechanisms have been computed by means of the standard fault plane fit PPFIT grid-search algorithm [Reasenber and Oppenheimer, 1985] using $M_D > 2.8$ events with more than 10 polarities. The

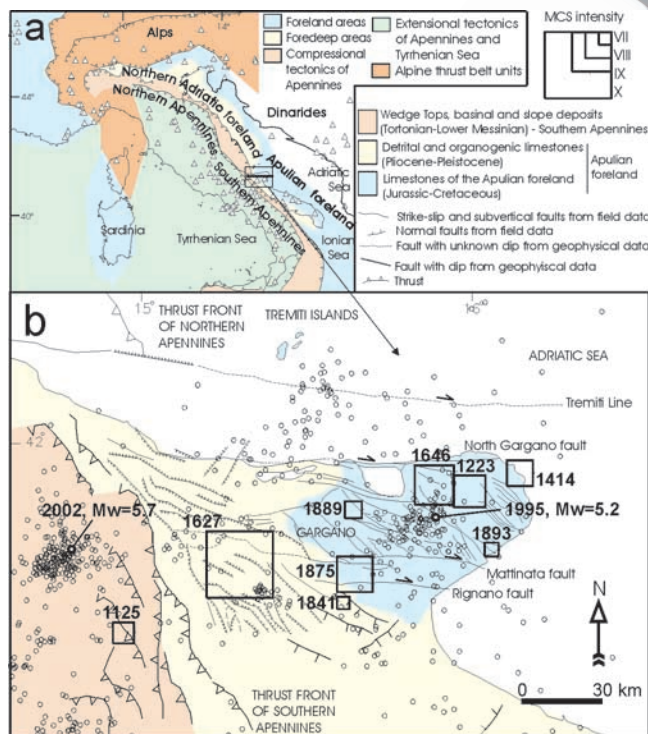


Figure 1. (a) Schematic drawing of the present-day geodynamics of Italy and surrounding regions [from Doglioni *et al.*, 1994; Oldow *et al.*, 2002]. Triangles are the seismic stations. (b) Structural sketch map of the Gargano region (data from Doglioni *et al.* [1994], Chilovi *et al.* [2000], and Patacca and Scandone [2004]). Epicenters of the 1981–2002 instrumental [Castello *et al.*, 2005] and historical [Gruppo di Lavoro CPTI, 1999] earthquakes is also reported.

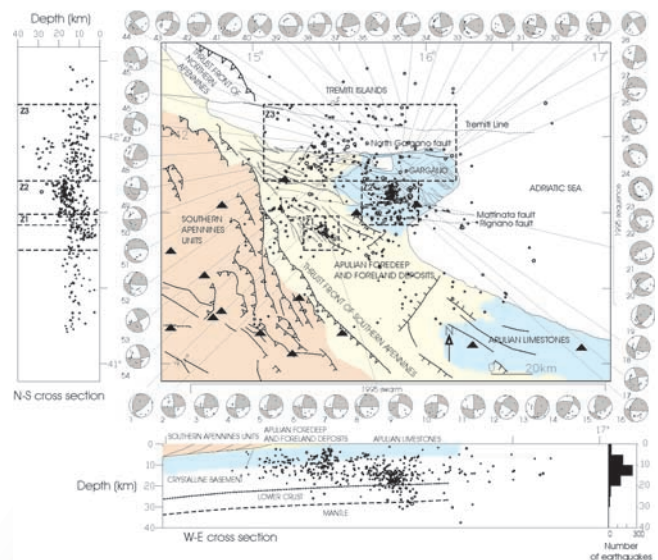


Figure 2. Map of the 1995–2004 relocated seismicity (dots) and calculated focal mechanisms superimposed on the structural scheme of the Gargano region (from Figure 1). Dots are proportional to MD. Z1, Z2 and Z3 represent the zones discussed in text. Seismic stations are reported as black triangles. Geological scheme reported in the E-W vertical section is modified from Chilovi *et al.* [2000]. The date, depth and M_D of the earthquakes for which the focal mechanisms were calculated is reported in Table S1 of the auxiliary material.¹

average errors on the maximum likelihood solutions were also computed by PPFIT and are less than 10 degree for strike, dip and rake, respectively. A standard technique of analysis of nodal planes is here applied to the 54 calculated focal mechanisms following the approach of Milano *et al.* [2005]. Focal mechanisms have been also used to compute the stress tensor following Gephart and Forsyth [1984].

3. Results

[7] The epicentral distribution of the about 500 best relocated events ($M_D \geq 1.9$) occurred between January 1995 and December 2004 in the sector $41^\circ 20' - 42^\circ 20' N$, $15^\circ - 16^\circ 50' E$ is shown in Figure 2. Almost all events located in Z1 zone (Figure 2) are relative to a seismic swarm occurred between June and August 1995 ($M_{Dmax} = 3.7$). This swarm, constituted by few tens of seismic events, shows a rough N-S alignment and overlaps the NW-SE to N-S striking faults located between GP and the thrust front of Southern Apennines. Focii range between 4 and 12 km (Figure 2). The events located in Z2 zone are related to a seismic sequence started with a M_W 5.2 event on 30 September 1995 and lasted until June 1996. Z2 earthquakes are located on the E-W striking Mattinata fault and on the NW-SE faults outcropping between the Mattinata fault and the North Gargano fault (Figure 2). The hypocenters of this sequence are deeper than those of the Z1

¹Auxiliary material is available at <ftp://ftp.agu.org/apend/gl/2005GL024604>.

Table 1. Velocity Model Used for Earthquakes Location

Depth to Top (km)	Velocity (V_p , km/s)
0	4.0
2	5.5
10	5.8
23	6.7
35	8.2
50	8.3

events, and concentrate between 15 and 25 km in depth, at the base of the upper crust (Figure 2). Outside Z1 and Z2, the remnant events are mainly located between the North Gargano fault and the Tremiti Line (Z3 zone in Figure 2). Z3 hypocenters are between 5 and 20 km of depth.

[8] P axes of the calculated fault plane solutions show a prevailing NW-SE strike, while T axes strike preferentially NE-SW (Figure 3a). This distribution indicates a prevailing strike-slip to oblique strain regime and no significant differences among the distributions of P and T axes in Z1, Z2 and Z3 events are recognized. Azimuthal distribution of nodal planes shows a maximum striking N-S for the Z1 focal solutions (Figure 3b). The nodal planes with this strike show rakes consistent with left-lateral to left-lateral/reverse slips (Figure 3c). Two maxima striking E-W and NNW-SSE are evidenced for the Z2 nodal planes (Figure 3b). The E-W striking planes have rakes consistent with prevailing right-lateral slips, whereas the NNW-SSE planes show rakes suggesting prevailing left-lateral slips (Figure 3c). Strikes of the Z3 nodal planes show a maximum at E-W (Figure 3b) and rakes consistent with prevailing right-lateral slips (Figure 3c). Results of the stress inversion (Figure 3d) indicate a strike-slip/reverse stress regime for Z1 focal solutions with $\sigma_1 = 137/6$ (trend/plunge) and $\sigma_3 = 44/27$. The inversion of the Z2 focal solutions is consistent with an oblique (normal/strike-slip) stress regime with $\sigma_1 = 260/63$ and $\sigma_3 = 39/30$. The Z3 stress tensor indicates a pure strike-slip regime with $\sigma_1 = 350/9$ and $\sigma_3 = 259/3$.

[9] The data presented here and those from the historical and instrumental catalogues [Gruppo di Lavoro CPTI, 1999; Castello et al., 2005] indicate that the temporal evolution of the GP seismicity in the last 25 years is mainly characterized by sparse isolated events. The events of the 1995 seismic sequence concentrate on the E-W and NW-SE faults (Figure 2). The larger historical earthquakes and the $M_D > 4$ events of the last 25 years occurred along the main fault segments [Gruppo di Lavoro CPTI, 1999].

4. Discussion and Conclusions

[10] The data presented here indicate that most of the seismicity recorded in the GP area of the Apulian foreland between 1995 and 2004 occurred in three zones: Z1, Z2 and Z3 (Figure 2). In Z1, the spatial distribution of the earthquakes, the preferred strike of nodal planes of focal mechanisms, and the depth of the events indicate that the Z1 seismicity mainly develops along N-S ruptures with left-lateral slips in a strike-slip/reverse stress regime (Figure 3c). Z1 seismicity develops within the Apulian limestones and crystalline basement of the foreland. Z2 epicenters overlap the E-W striking Mattinata and Rignano faults and the NW-SE faults. The preferred strikes of the Z2 nodal planes are consistent with those of these faults. As a result, we propose

that the Z2 seismicity develops along the E-W faults that bound the southern sector of GP and along the NW-SE faults. These faults move in response to a normal/strike-slip stress regime characterized by a NE-SW extension. This direction of extension is consistent with results from GPS surveys [Anzidei et al., 1996; Battaglia et al., 2004] and with mesostructural data collected on Quaternary terrains of the Mattinata fault [Chilovi et al., 2000]. The E-W striking GP ruptures have right-lateral slips (see also Figure 3b), while the NW-SE ruptures show normal to left-lateral slips. In this picture, the NW-SE ruptures may be interpreted as T-type and X-type shears related to a main E-W shear zone, according to experimental models on shear zones [Bartlett et al., 1981]. The more widespread Z3 seismicity is confined between the E-W striking Tremiti Line and North Gargano fault, and the azimuthal distribution of the Z3 nodal planes also follows this preferred strike. This suggests that the Z3 ruptures develops along E-W, right-lateral

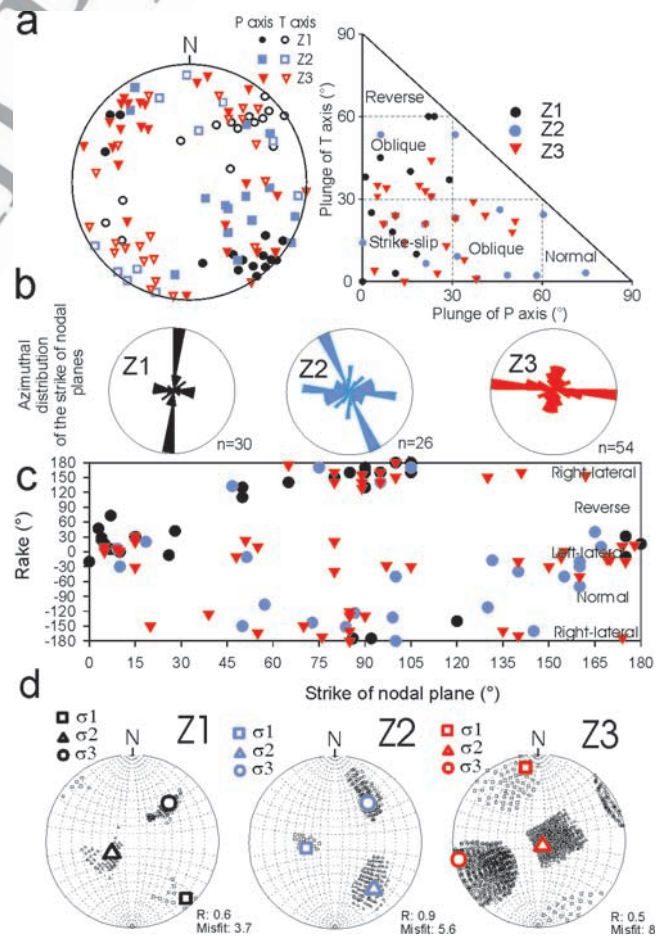


Figure 3. (a) Distribution of the P and T axes of the 54 focal mechanisms reported in Figure 2 on a Schimidt net (lower hemisphere) (right) and on a plunge of P axis vs. plunge of T axis plot. (b) Azimuthal distribution of the strike of nodal planes of focal solutions in Z1, Z2 and Z3. (c) Strike vs. rake of nodal planes of focal solutions in Z1, Z2 and Z3. (d) Results of the stress inversion [Gephart and Forsyth, 1984] of focal mechanisms of earthquakes in Z1, Z2 and Z3. 95% confidence limits for each of the three axes is also reported.

shears that move in response to a NNW-SSE compression (Figure 3d).

[11] The structural evolution the GP shear zone [Chilovi *et al.*, 2000; Brankman and Aydin, 2004] is characterized by E-W, left-lateral faults moving in response to a NE-SW compression from Late Miocene to Early Pliocene times and by Late Pliocene to Quaternary reactivations with opposite (dextral) slip sense. The Z2 and Z3 stress fields and the kinematics of the ruptures deduced from the last nine years of seismicity (Figure 3) testify the present-day dextral slips of the main GP, E-W striking faults, that move in response to a NW-SE compression (i.e., NE-SW extension). The Z2 seismicity concentrates between 15 and 25 km of depth and extends up to 30 km, so affecting the deeper layers of the crust (Figure 2b). We conclude that the GP shear zone represents a major, deep crustal discontinuity that, according to Doglioni *et al.* [1994], separates the subsiding northern Adriatic foreland from the uplifting, Apulian foreland (see Figure 1). This different behaviour is due to the higher hinge rollback of the Adriatic foreland with respect to the buckled Apulian foreland. This process is responsible for the higher, northeastward propagation velocity of the thrust front of Northern Apennines with respect to that of Southern Apennines. The different propagation velocity of the thrust fronts accounts for the active, dextral strike-slip tectonics of GP.

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